Submitted to AJ on 2010/09/25, accepted 2011/01/25

ExploreNEOs III: Physical characterization of 65 low-deltaV NEOs

Michael Mueller[1]

M. Delbo'[1]

J.L. Hora[2]

D.E. Trilling[3]

B. Bhattacharya[4]

W.F. Bottke[5]

S. Chesley[6]

J.P. Emery[7]

G. Fazio[2]

A.W. Harris[8]

A. Mainzer[6]

M. Mommert[8]

B. Penprase[9]

H.A. Smith[2]

T.B. Spahr[2]

J.A. Stansberry[10]

and

C.A. Thomas[3]

ABSTRACT

Space missions to NEOs are being planned at all major space agencies, and recently a manned mission to an NEO was announced as a NASA goal. Efforts to find and select suitable targets (plus backup targets) are severely hampered by our lack of knowledge of the physical properties of dynamically favorable NEOs. In particular, current mission scenarios tend to favor primitive low-albedo objects. For the vast majority of NEOs the albedo is unknown.

Here we report new constraints on the size and albedo of 65 NEOs with rendezvous deltaV < 7 km/s. Our results are based on thermal-IR flux data obtained in the framework of our ongoing (2009–2011) ExploreNEOs survey (Trilling et al. 2010) using NASA's "Warm Spitzer" space telescope. As of 2010 July 14, we have results for 293 objects in hand (including the 65 low-deltaV NEOs presented here); before the end of 2011 we expect to have measured the size and albedo of ~ 700 NEOs (including probably ~ 160 low-deltaV NEOs).

While there are reasons to believe that primitive volatile-rich materials are universally low in albedo, the converse need not be true: the orbital evolution of some dark objects likely has caused them to lose their volatiles by coming too close to the Sun. For all our targets, we give the closest perihelion distance they are likely to have reached (using orbital integrations from Marchi et al. 2009) and corresponding upper limits on the past surface temperature. Low-deltaV objects for which both albedo and thermal history may suggest a primitive composition include (162998) 2001 SK162, (68372) 2001 PM9, and (100085) 1992 UY4.

Subject headings: infrared: planetary systems — minor planets, asteroids: general — radiation mechanisms: thermal — space vehicles — surveys

---

[1]UNS-CNRS-Observatoire de la Côte d'Azur, Laboratoire Cassiopée, BP 4229, 06304 Nice cedex 04, France; michael.mueller@oca.eu

[2]Harvard-Smithsonian Center for Astrophysics, 60 Garden St., MS-65, Cambridge, MA 02138

[3]Department of Physics and Astronomy, Northern Arizona University, Flagstaff, AZ 86001

[4]NASA Herschel Science Center, Caltech, M/S 100-22, 770 South Wilson Ave. Pasadena, CA 91125 USA

[5]Southwest Research Institute, 1050 Walnut St, Suite 300, Boulder, Colorado 80302, USA

[6]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA

[7]Department of Earth and Planetary Sciences, University of Tennessee, 1412 Circle Dr., Knoxville, TN 37996

[8]DLR Institute of Planetary Research, Rutherfordstrasse 2, 12489 Berlin, Germany.

[9]Department of Physics and Astronomy, Pomona College, 610 N. College Ave, Claremont, CA 91711

[10]Steward Observatory, University of Arizona, 933 N. Cherry Ave, Tucson AZ 85721

1. Introduction

To date, two near-Earth objects (NEOs) have been targeted by space missions, both yielding a wealth of fascinating and groundbreaking insights into the past and current state of the Solar System: NASA's Near-Shoemaker mission went into orbit around its target (433) Eros in 2000 and landed on it in the following year; the Japanese mission Hayabusa arrived at (25143) Itokawa in 2005 and scrutinized the NEO for a few months. In June 2010, Hayabusa succeeded in returning asteroid dust samples to Earth.

Given the remarkable success of these missions it is perhaps not surprising that robotic NEO mission concepts are being considered at space agencies across the planet, including NASA's OSIRIS-REx, JAXA's Hayabusa 2, and ESA's Marco Polo (see, e.g., Lauretta et al. 2010; Okada et al. 2010; Michel et al. 2009, for recent updates on these missions). In a speech in April 2010, President Obama announced the goal of a manned space mission to an asteroid (see Abell et al. 2009, for a corresponding NASA mission scenario including robotic precursor missions).

Finding a suitable target asteroid is one of the challenging aspects of mission planning. Targets are tightly constrained in terms of their orbital dynamics and physical properties. Furthermore, launch windows are usually tight and the planning process long. Unforeseen delays due to technological or financial problems risk eliminating the nominal target; it is therefore generally advisable to plan for contingency or backup targets.

Dynamics, Δv: As discussed by Shoemaker & Helin (1978), mission cost depends chiefly on the required amount of propellant, which follows from the total specific linear momentum, Δv, that must be imparted on the spacecraft for it to reach the target orbit. Minimizing Δv is therefore a top priority for practical reasons. It is worth emphasizing that there are a large number of NEOs that are reachable at a lower Δv than that required to reach Mars.

A realistic assessment of Δv depends on the specific mission scenario and timing, and must be evaluated on a target-by-target basis. A customary first-order estimate is the Δv of a Hohmann transfer orbit, which is an analytic function of the orbital elements (see Shoemaker & Helin 1978). Thus, in a first target selection process objects with sufficiently small "Hohmann-Δv" are identified. Only those objects need to be studied in detail. For the purposes of this study, we will refer to the "Hohmann-Δv" as Δv (without qualifiers).

Physical properties: For the vast majority of NEOs, including low-Δv objects, nothing is known about their physical properties. Frequently, however, mission concepts require the target to be within a given size or mass range, e.g., in order to enable the spacecraft to orbit the target. Moreover, the science goals of some current mission scenarios require their target to be a "primitive" object, translating into constraints on their albedo and thermal history (see below).

Primitive objects: Some meteorites contain surprisingly pristine material that has suffered very little modification since the early days of the Solar System. Their asteroidal parent bodies are of particular interest for some NEO missions (especially since both NEAR-Shoemaker and Hayabusa targeted S-type asteroids, which have undergone significant processing).

Judging from meteorite analogues, asteroids with very low albedo (geometric albedo $p_V \lesssim 7.5$ %) are very likely to be "primitive" and vice-versa (Fernández et al. 2005). A word of caution applies to NEOs, however: their relative proximity to the Sun can potentially cause their surfaces to heat up to the point that thermal surface alterations occur (de-volatilization, chemical reactions, etc.). There are hence two necessary conditions for an NEO to have a primitive surface: a low albedo and an orbital history that never brought the perihelion too close to the Sun.

ExploreNEOs: This is the third paper describing results from the ongoing (2009–2011) ExploreNEOs survey (following Trilling et al. 2010; Harris et al. 2011). The primary goal of this survey is to measure the size and albedo of $\sim$ 700 NEOs based on observations with NASA's "Warm Spitzer" space telescope. Trilling et al. (2010) describe the goals and methods of the survey along with results for the first 101 NEOs; Harris et al. (2011) check the accuracy of the ExploreNEOs results against values published in the literature (where available) and find diameters to be typically consistent within 20%, albedos within 50%.

As of 2010 July 14, we have data for 293 NEOs in hand including 65 objects with $\Delta v < 7$ km/s. By the end of the survey, i.e. before the end of 2011, we expect to have measured $\sim$ 160 low-Δv objects. We chose to publish this first batch of results in order to alert the community to the existence of our growing database of characterized low-Δv objects.

Overview of this work: In Section 2 we describe our photometric data. Our modeling approach is described in Section 3, and resulting diameter and albedo estimates are presented in Section 4. In Section 5 we study the thermal history of our targets. We discuss the implications of our results in Section 6 and summarize our conclusions in Section 7.

2. Warm-Spitzer observations

The observations reported herein use the post-cryogenic ("warm") mode of the IRAC camera (Fazio et al. 2004) onboard the Spitzer Space Telescope (Werner et al. 2004). Each NEO target is observed in the two photometric channels (channels 1 and 2) with central wavelengths of around 3.6 and 4.5 μm, respectively. Observations are built up from frames that alternate repeatedly between the two channels, such that the resulting fluxes are quasi-simultaneous. Further details on our observation design and data reduction are given in Trilling et al. (2010).

Table 1. Spitzer data sorted by Δv

Δv (km/s)	Object	Time (UT)	H	r (AU)	Δ (AU)	α (deg.)	f36 (mJy)	f45 (mJy)
4.632	(25143) Itokawa	2010-May-15 14:45:09	19.20	1.018	0.052	74.56	1.767 ± 0.041	6.033 ± 0.072
4.755	1996 XB27	2010-Jul-12 06:41:36	21.84	1.121	0.192	51.92	0.0178 ± 0.0040	0.0428 ± 0.0061
4.887	(10302) 1989 ML	2009-Aug-21 03:09:35	19.50	1.100	0.152	56.01	0.229 ± 0.015	0.560 ± 0.022
5.276	(99799) 2002 LJ3	2009-Sep-19 22:38:44	18.10	1.238	0.354	46.18	0.125 ± 0.015	0.392 ± 0.020
5.280	2001 CQ36	2010-Apr-15 13:27:01	22.45	1.069	0.125	55.50	0.0215 ± 0.0044	0.0787 ± 0.0081
5.302	(52381) 1993 HA	2009-Nov-18 12:09:41	20.20	1.257	0.402	46.59	0.0303 ± 0.0052	0.150 ± 0.011
5.328	2000 YF29	2010-Feb-20 04:43:34	20.16	1.015	0.123	83.03	0.131 ± 0.012	0.467 ± 0.020
5.391	(1943) Anteros	2009-Sep-15 00:09:47	15.75	1.548	0.951	40.17	0.189 ± 0.013	0.582 ± 0.022
5.486	(138911) 2001 AE2	2009-Aug-13 14:53:36	19.10	1.330	0.483	41.78	0.0244 ± 0.0047	0.0888 ± 0.0086
5.487	2006 SY5	2009-Jul-30 18:18:27	22.08	1.093	0.136	54.07	0.0312 ± 0.0051	0.1167 ± 0.0097
5.555	(162416) 2000 EH26	2010-Apr-29 07:39:49	21.70	1.125	0.217	51.21	0.0378 ± 0.0058	0.1181 ± 0.0099
5.565	(162998) 2001 SK162	2009-Dec-17 23:35:37	18.00	1.135	0.451	63.68	0.815 ± 0.028	3.184 ± 0.051
5.653	(68372) 2001 PM9	2009-Aug-20 10:32:54	18.90	1.130	0.204	53.62	3.928 ± 0.059	19.61 ± 0.14
5.719	(12923) Zephyr	2010-May-21 04:54:42	16.10	1.477	0.876	41.50	0.253 ± 0.021	0.453 ± 0.023
6.041	(85938) 1999 DJ4	2009-Aug-13 15:40:17	18.60	1.409	0.688	43.10	0.0172 ± 0.0039	0.0620 ± 0.0072
6.069	(433) Eros	2009-Aug-25 06:16:47	11.16	1.702	1.218	36.50	13.99 ± 0.11	40.23 ± 0.20
6.070	2000 GV147	2009-Oct-24 06:09:17	19.03	1.064	0.336	74.34	0.0998 ± 0.010	0.337 ± 0.017
6.086	2000 XK44	2010-Jan-11 03:12:17	17.73	1.288	0.848	51.85	0.0285 ± 0.0051	0.1040 ± 0.0094
6.106	1993 RA	2009-Nov-17 02:57:14	18.91	1.191	0.587	59.20	0.0165 ± 0.0039	0.0544 ± 0.0068
6.130	(177614) 2004 HK33	2009-Jul-30 16:25:59	17.60	1.057	0.095	63.88	5.895 ± 0.071	22.92 ± 0.14
6.191	1998 VO	2009-Dec-13 03:44:37	20.37	1.024	0.021	76.62	4.481 ± 0.063	15.31 ± 0.11
6.196	2006 SV19	2009-Sep-15 16:08:48	17.76	1.166	0.672	60.97	0.109 ± 0.010	0.435 ± 0.019
6.236	2005 JA22	2009-Nov-10 03:50:52	18.47	1.296	0.489	46.66	0.0908 ± 0.0093	0.319 ± 0.017
6.240	(1627) Ivar	2010-Jun-16 08:39:40	13.20	1.933	1.249	27.62	1.264 ± 0.033	2.670 ± 0.048
6.279	(87024) 2000 JS66	2010-Jan-10 19:24:49	18.70	1.104	0.567	65.82	0.0163 ± 0.0023	0.0427 ± 0.0061
6.323	(22099) 2000 EX106	2010-Jan-11 09:47:46	18.00	1.029	0.246	79.60	0.225 ± 0.015	0.842 ± 0.027
6.364	2003 SL5	2009-Sep-19 23:06:19	19.14	1.114	0.164	53.62	0.289 ± 0.017	1.052 ± 0.029
6.364	(35107) 1991 VH	2010-Mar-20 17:04:49	16.90	1.172	0.660	58.78	0.113 ± 0.011	0.477 ± 0.021
6.379	(172974) 2005 YW55	2010-Mar-24 09:16:52	19.30	1.242	0.386	44.41	0.0615 ± 0.0078	0.171 ± 0.013
6.405	(65679) 1989 UQ	2009-Oct-15 20:50:49	19.40	1.129	0.237	58.64	0.405 ± 0.061	2.264 ± 0.043
6.431	(159402) 1999 AP10	2009-Aug-31 22:54:55	16.40	1.292	0.838	52.32	0.090 ± 0.010	0.278 ± 0.016
6.491	(143651) 2003 QO104	2009-Aug-21 02:40:17	16.00	1.402	0.801	45.93	0.276 ± 0.042	1.052 ± 0.031
6.507	1989 AZ	2010-Feb-19 07:05:07	19.49	1.003	0.044	93.49	8.998 ± 0.090	46.28 ± 0.19
6.512	2006 WO127	2009-Nov-04 01:09:24	16.18	1.528	0.889	40.23	0.102 ± 0.011	0.350 ± 0.018
6.516	(140158) 2001 SX169	2010-Jan-26 04:30:24	18.30	1.253	0.430	47.17	0.092 ± 0.010	0.362 ± 0.018
6.526	(100085) 1992 UY4	2010-Feb-07 01:04:57	17.80	1.226	0.832	54.76	0.317 ± 0.017	1.694 ± 0.037
6.534	(85839) 1998 YO4	2010-Apr-05 10:55:52	16.30	1.326	0.783	48.87	0.179 ± 0.014	0.792 ± 0.026
6.539	(68359) 2001 OZ13	2010-May-26 02:33:35	17.60	1.520	0.896	39.56	0.0243 ± 0.0079	0.0443 ± 0.0078
6.577	(11398) 1998 YP11	2010-Apr-11 12:59:19	16.30	1.480	0.700	36.03	0.240 ± 0.016	0.830 ± 0.027
6.608	(155334) 2006 DZ169	2009-Dec-20 23:59:59	17.10	1.636	0.871	32.65	0.0548 ± 0.0072	0.148 ± 0.011
6.609	(175706) 1996 FG3	2010-May-02 05:19:51	18.20	1.213	0.418	51.02	0.853 ± 0.028	4.391 ± 0.062
6.610	(52760) 1998 ML14	2010-Jan-26 05:06:11	17.50	1.075	0.484	69.33	0.127 ± 0.012	0.463 ± 0.020
6.628	(138947) 2001 BA40	2010-Jan-10 17:16:01	18.40	1.173	0.721	59.14	0.0135 ± 0.0035	0.0592 ± 0.0071
6.652	2002 QE7	2009-Sep-23 04:42:21	19.33	1.217	0.329	47.87	0.0662 ± 0.0080	0.188 ± 0.013
6.652	(5626) 1991 FE	2009-Aug-21 03:23:36	14.70	1.689	0.972	33.08	0.434 ± 0.020	1.209 ± 0.031

In this work, we restrict ourselves to objects observed on or before 2010 July 14 with a rendezvous $\Delta v \leq 7$ km/s. Δv values are taken from Lance Benner's online list of Δv for all NEOs,[1] which is calculated from the orbital elements and the Shoemaker & Helin (1978) formalism.

In Table 1 we present the measured in-band fluxes and the observing circumstances as taken from JPL's *Horizons* ephemeris server. H magnitudes are assumed to be uncertain by 0.5 mag (see Section 3). Observations carried out on or before 2009 November 4 have been presented in Trilling et al. (2010), later observations are new here.

3. Thermal modeling

We use an updated version of the thermal-modeling pipeline used in previous publications resulting from the ExploreNEOs survey (Trilling et al. 2010; Harris et al. 2011). For completeness, we briefly summarize the more detailed description given in Trilling et al. (2010). Section 3.1 presents the updates relative to the previous pipeline, chiefly an estimation of the statistical uncertainty of our results. Due to said update, some of our results differ slightly (but within the error bars) from the preliminary results given in Trilling et al. (2010). A reanalysis of our entire data set is deferred to a later work.

NEO fluxes at Warm-Spitzer wavelengths have significant contributions from reflected sunlight and from thermal emission. We are interested in the latter in order to calculate the target size and albedo using a thermal model. Therefore, in a first step, we estimate the amount of reflected solar radiation using the method first described by Mueller et al. (2007), then refined in Trilling et al. (2008, 2010). Briefly, we calculate the expected V magnitude based on the observing circumstances given in Table 1 and extrapolate to 3.6 and 4.5 μm fluxes using published values of the solar flux at those wavelengths and the Sun's V magnitude. We also assume the spectral reflectivity at Warm Spitzer wavelengths to be 1.4 times that in the V band (see Trilling et al. 2008; Harris et al. 2009; Trilling et al. 2010). In-band thermal flux equals total flux minus reflected flux. In rare cases, the calculated reflected flux exceeds the measured flux, leading to unphysical negative thermal fluxes in channel 1. In these cases (which we expect are due to inaccurate H magnitudes and/or lightcurve effects), we drop the channel-1 flux from the thermal analysis.

In-band thermal fluxes are color corrected to take account of the spectral breadth of IRAC's filters and the significant difference between the spectral shape of asteroidal thermal emission and the stellar-like spectrum assumed in IRAC flux calibration; color-correction factors for the reflected solar component are negligible. Color-correction factors are calculated for each target using the IRAC passbands given by Carey et al. (2010), the observing circumstances, and a suitable thermal model. As found by Mueller et al. (2007), the dependence of color-correction factors on the physical properties of the asteroid can be neglected.

[1] `http://echo.jpl.nasa.gov/~lance/delta_v/delta_v.rendezvous.html`

Table 1—Continued

Δv (km/s)	Object	Time (UT)	H	r (AU)	Δ (AU)	α (deg.)	f36 (mJy)	f45 (mJy)
6.661	(66251) 1999 GJ2	2010-Feb-09 16:33:48	17.00	1.751	1.038	30.67	0.0294 ± 0.0052	0.0512 ± 0.0066
6.692	(85990) 1999 JV6	2010-Jul-12 14:35:39	20.00	1.062	0.116	62.78	0.978 ± 0.029	4.922 ± 0.064
6.703	1998 SE36	2010-Apr-28 10:35:18	19.32	1.294	0.457	42.22	0.0280 ± 0.0050	0.1089 ± 0.0096
6.738	(5645) 1990 SP	2010-Jun-15 07:08:46	17.00	1.780	1.095	30.80	0.0496 ± 0.0071	0.237 ± 0.015
6.747	(3671) Dionysus	2010-Jun-12 23:01:07	16.30	1.136	0.518	62.60	0.180 ± 0.013	0.390 ± 0.019
6.750	2002 HF8	2009-Aug-24 23:44:37	18.27	1.262	0.449	48.69	0.1093 ± 0.0099	0.455 ± 0.020
6.751	(164202) 2004 EW	2009-Aug-06 05:32:19	20.80	1.049	0.158	75.37	0.0459 ± 0.0062	0.135 ± 0.010
6.757	2002 UN3	2010-Feb-12 22:31:31	18.60	1.325	0.503	41.88	0.0343 ± 0.0058	0.0555 ± 0.0070
6.791	(90373) 2003 SZ219	2009-Dec-20 00:33:14	18.80	1.313	0.466	42.42	0.0332 ± 0.0057	0.0686 ± 0.0078
6.817	(40329) 1999 ML	2009-Sep-03 00:25:51	17.70	1.344	0.501	41.48	0.197 ± 0.014	0.623 ± 0.023
6.828	(6239) Minos	2010-Mar-20 17:55:44	17.90	1.122	0.340	61.27	0.114 ± 0.012	0.28 ± 0.17
6.830	2005 EJ	2010-Mar-19 13:32:33	19.87	1.225	0.414	49.10	0.0215 ± 0.0046	0.0530 ± 0.0067
6.840	(5646) 1990 TR	2009-Dec-01 18:48:50	14.30	1.857	1.679	33.09	0.0393 ± 0.0063	0.0809 ± 0.0085
6.865	2003 WO7	2009-Oct-09 15:38:14	18.91	1.237	0.418	50.83	0.225 ± 0.022	0.517 ± 0.024
6.867	1999 RH33	2010-Apr-04 02:25:30	19.13	1.286	0.463	43.65	0.0177 ± 0.0042	0.0371 ± 0.0057
6.963	(10115) 1992 SK	2010-Apr-13 09:53:12	17.00	1.170	0.307	50.53	0.549 ± 0.024	1.896 ± 0.042
6.963	2003 BT47	2010-Apr-21 05:07:07	17.42	1.289	0.588	48.67	0.174 ± 0.013	0.670 ± 0.024
6.974	(5620) Jasonwheeler	2009-Aug-25 07:00:34	17.00	1.321	0.620	48.68	0.258 ± 0.016	1.252 ± 0.033
6.981	(152563) 1992 BF	2010-Apr-03 23:55:21	19.80	1.125	0.236	53.50	0.282 ± 0.017	1.377 ± 0.034
6.994	(138971) 2001 CB21	2009-Dec-06 22:09:34	18.40	1.033	0.272	79.87	0.176 ± 0.014	0.591 ± 0.023

Note. — Times given are roughly mid-observation as measured on Spitzer. H is the absolute optical magnitude (taken from *Horizons* and assumed to be uncertain by ± 0.5 mag). r and Δ are heliocentric and Spitzer-centric distance, resp., α is the solar phase angle. f36 and f45 are the flux at ~ 3.6 and 4.5 μm, resp. (channels 1 and 2).

Diameter and albedo are estimated from the final thermal fluxes using the NEATM (Harris 1998). The NEATM contains a dimensionless parameter η that describes the effective surface temperature. Trilling et al. (2008) found that data quality does not usually allow to fit η to Warm-Spitzer data of NEOs, but that reasonable estimates of diameter and albedo can still be obtained by assuming an empirical linear relationship between η and solar phase angle α. That relationship was established by Delbo' et al. (2003); here we use an updated relationship (based on a slightly larger data set) by Wolters et al. (2008):

$$\eta = (0.91 \pm 0.17) + (0.013 \pm 0.004)\alpha \text{ (in deg.).} \tag{1}$$

3.1. Monte-Carlo approach

In order to provide a realistic estimate of the uncertainty in our diameter and albedo results, we use a Monte-Carlo approach in which various sources of uncertainty are considered: the measured flux uncertainty, the calibration uncertainty of 5 % (Carey et al. 2010), the uncertainty in H (see below), and the NEATM temperature parameter η (which is assumed to vary by ± 0.3 around its nominal value; see below). For each observation, we generate 1000 sets of random synthetic fluxes normally distributed about the measured value and with a standard deviation equal to the root-sum-square of the measured flux uncertainty and the 5 % calibration uncertainty. Analogously, Gaussian distributions of H and η values are used in the fit. The distribution of albedo results (diameters to a lesser extent) is strongly non-Gaussian, see Fig. 1. We hence adopt the median of our Monte-Carlo results as the nominal value and asymmetric error bars to encompass the central 68.2 % of the results. Additionally, we determine the percentage of albedo results falling into albedo bins (see Section 4).

ΔH: In the analysis of purely thermal observations of asteroids, H is known to have a negligible influence on best-fit diameters but impacts p_V directly (Harris & Harris 1997). In our case, however, H is also used in correcting for reflected solar flux and hence influences the calculated thermal flux contribution. We therefore decided to vary H within the Monte-Carlo fit. The correction for reflected sunlight becomes more critical as more reflected sunlight is contained within the measured flux; it is hence particularly important for high-albedo objects and for objects observed at large heliocentric distance.

Propagating ΔH into thermal-flux uncertainties is an update of the thermal-modeling pipeline relative to Trilling et al. (2010). While this does not change the calculated nominal thermal fluxes, it does change their uncertainties and hence the relative weight with which they enter the χ^2 minimization procedure, leading to somewhat different diameter and albedo results. For practically all targets, however, the corresponding diameter change is < 1 % and hence negligible.

For most of our targets, published values for H, let alone ΔH, are unavailable. An observing campaign to measure H for a number of our targets is currently underway; results will be reported

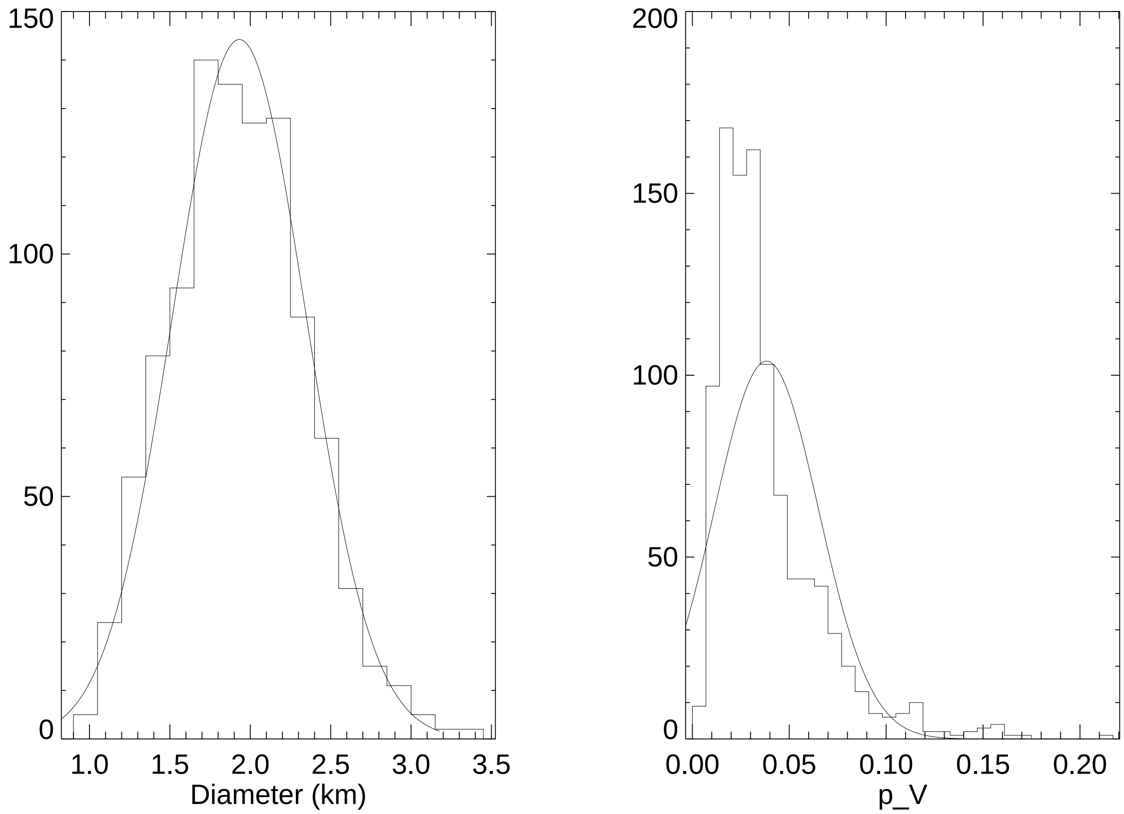

Fig. 1.— Histogram of the distribution of diameter and albedo values resulting from the Monte-Carlo procedure for 2001 SK162. Both histograms are overplotted with the respective best-fit Gaussian functions. Note that the diameter distribution is rather consistent with being normally distributed, while the albedo distribution is clearly not.

in a separate paper. For the time being, we fall back to the approximative H values given by the *Horizons* ephemeris server which are notoriously unreliable[2] (see Jurić et al. 2002; Parker et al. 2008). For now, we adopt $\Delta H = 0.5$ mag throughout, see Section 4.1 for exceptions.

$\Delta\eta$: Changes in the assumed η value lead to significant changes in diameter and albedo, see e.g. Harris et al. (2011). The quoted uncertainties in Equation (1) lead to a final $\Delta\eta \sim 0.3$ for $\alpha \sim 50°$, a typical value for our sample. This uncertainty estimate is corroborated by Ryan & Woodward (2010), who found a typical η value of 1.07 ± 0.27; we caution, however, that their sample is dominated by large main-belt asteroids, whose thermal properties are rather distinct from our

[2]It should not be forgotten that *Horizons* is not designed to calculate H magnitudes but ephemerides, at which it does an excellent job.

sample of small NEOs. For our Monte-Carlo analysis, we therefore adopt a Gaussian distribution of η values scattering about the nominal value of $0.91 + 0.013\alpha$ with a standard deviation of 0.3. Unphysical η values below 0.5 are discarded.

4. Sizes and albedos

Our diameter and albedo results are given in Table 2 along with their statistical uncertainties estimated from the Monte-Carlo analysis described above. In order to illustrate the implications of our albedo results on surface mineralogy, we also determine the probabilities p_1–p_4 with which the albedo falls within one of four albedo bins; these probabilities are estimated as the fraction of Monte-Carlo albedos falling within the respective bin. The albedo bins are designed to correspond to taxonomic types as closely as possible, particularly for the purpose of identifying primitive NEOs:

- $p_V < 7.5$ %: As shown by Fernández et al. (2005), albedos in this range strongly indicate a primitive surface composition
- 7.5 % $\leq p_V <$ 15 %: While objects in this albedo range are still likely to be primitive, some of them may be more akin to (silicate rich) S types
- 15 % $\leq p_V <$ 30 % Objects in this albedo range are most likely S or Q types (or M types, but those are relatively rare among NEOs)
- 30 % $\leq p_V$ More exotic compositions, e.g. E types.

Table 2. Results of our Spitzer observations and of the dynamical analysis described in Section 5

Δv (km/s)	Object	D (km)	p_V	p_1	p_2	p_3	p_4	$q_{10\%}$ (AU)	$q_{50\%}$ (AU)	$q_{90\%}$ (AU)	$T_{10\%}$ (K)	$T_{50\%}$ (K)	$T_{90\%}$ (K)
4.632	(25143) Itokawa	$0.319^{+0.045}_{-0.050}$	$0.41^{+0.20}_{-0.18}$	0.003	0.017	0.277	0.703	0.376	0.737	0.887	644	460	419
4.755	1996 XB27	$0.084^{+0.013}_{-0.012}$	$0.48^{+0.26}_{-0.19}$	0.000	0.017	0.167	0.817	0.612	0.658	1.000	501	483	392
4.887	(10302) 1989 ML	$0.248^{+0.035}_{-0.043}$	$0.47^{+0.28}_{-0.19}$	0.000	0.010	0.180	0.810	0.279	0.673	1.000	743	478	392
5.276	(99799) 2002 LJ3	$0.503^{+0.094}_{-0.085}$	$0.43^{+0.22}_{-0.18}$	0.000	0.033	0.233	0.733	0.313	0.665	0.875	704	483	421
5.280	2001 CQ36	$0.068^{+0.011}_{-0.012}$	$0.41^{+0.29}_{-0.16}$	0.000	0.030	0.223	0.747	0.145	0.579	1.000	1038	519	395
5.302	(52381) 1993 HA	$0.337^{+0.097}_{-0.078}$	$0.140^{+0.110}_{-0.077}$	0.210	0.337	0.357	0.097	0.258	0.668	0.874	802	498	435
5.328	2000 YF29	$0.244^{+0.041}_{-0.038}$	$0.251^{+0.154}_{-0.095}$	0.003	0.140	0.487	0.370	0.229	0.663	0.838	840	494	439
5.391	(1943) Anteros	$2.48^{+0.69}_{-0.60}$	$0.145^{+0.146}_{-0.073}$	0.183	0.330	0.350	0.137	0.313	0.665	0.875	727	499	435
5.486	(138911) 2001 AE2	$0.352^{+0.073}_{-0.069}$	$0.34^{+0.22}_{-0.16}$	0.000	0.090	0.337	0.573	0.310	0.627	0.885	715	503	423
5.487	2006 SY5	$0.090^{+0.013}_{-0.017}$	$0.34^{+0.23}_{-0.14}$	0.007	0.083	0.320	0.590	0.302	0.572	0.879	725	527	425
5.555	(162416) 2000 EH26	$0.141^{+0.026}_{-0.024}$	$0.181^{+0.142}_{-0.073}$	0.053	0.313	0.443	0.190	0.289	0.775	0.901	754	460	427
5.565	(162998) 2001 SK162	$1.94^{+0.38}_{-0.37}$	$0.031^{+0.028}_{-0.015}$	0.920	0.077	0.003	0.000	0.244	0.793	0.967	834	462	418
5.653	(68372) 2001 PM9	$1.73^{+0.45}_{-0.41}$	$0.0180^{+0.0170}_{-0.0080}$	0.970	0.030	0.000	0.000	0.278	0.711	0.872	782	488	441
5.719	(12923) Zephyr	$1.86^{+0.45}_{-0.46}$	$0.21^{+0.17}_{-0.11}$	0.070	0.247	0.410	0.273	0.304	0.714	0.903	733	478	425
6.041	(85938) 1999 DJ4	$0.478^{+0.100}_{-0.082}$	$0.28^{+0.23}_{-0.13}$	0.017	0.140	0.393	0.450	0.303	0.690	0.882	729	482	427
6.069	(433) Eros	$30.7^{+10.0}_{-8.3}$	$0.065^{+0.075}_{-0.034}$	0.560	0.303	0.117	0.020	0.320	0.580	0.742	724	538	476
6.070	2000 GV147	$0.502^{+0.104}_{-0.072}$	$0.185^{+0.124}_{-0.084}$	0.063	0.300	0.460	0.177	0.263	0.577	0.820	791	534	447
6.086	(217807) 2000 XK44	$0.73^{+0.14}_{-0.13}$	$0.28^{+0.18}_{-0.12}$	0.013	0.130	0.387	0.470	0.319	0.617	0.925	711	510	417
6.106	1993 RA	$0.358^{+0.063}_{-0.052}$	$0.40^{+0.23}_{-0.16}$	0.007	0.040	0.300	0.653	0.323	0.713	0.924	697	468	411
6.130	(177614) 2004 HK33	$0.94^{+0.17}_{-0.18}$	$0.189^{+0.141}_{-0.081}$	0.073	0.267	0.457	0.203	0.306	0.638	0.820	732	507	447
6.191	(192559) 1998 VO	$0.216^{+0.032}_{-0.032}$	$0.30^{+0.17}_{-0.13}$	0.007	0.107	0.380	0.507	0.247	0.521	0.745	805	554	463
6.196	(212546) 2006 SV19	$1.06^{+0.23}_{-0.21}$	$0.129^{+0.104}_{-0.058}$	0.183	0.420	0.297	0.100	0.216	0.809	1.000	876	453	407
6.236	2005 JA22	$0.67^{+0.17}_{-0.14}$	$0.164^{+0.117}_{-0.078}$	0.120	0.320	0.423	0.137	0.200	0.747	0.970	908	470	412
6.240	(1627) Ivar	$9.4^{+3.9}_{-2.3}$	$0.094^{+0.138}_{-0.051}$	0.390	0.297	0.253	0.060	0.347	0.681	0.840	695	496	446
6.279	(87024) 2000 JS66	$0.312^{+0.059}_{-0.039}$	$0.63^{+0.34}_{-0.23}$	0.000	0.003	0.057	0.940	0.279	0.598	0.874	728	497	411
6.323	(22099) 2000 EX106	$0.621^{+0.109}_{-0.076}$	$0.29^{+0.16}_{-0.12}$	0.003	0.113	0.413	0.470	0.138	0.530	0.804	1080	550	446
6.364	2003 SL5	$0.337^{+0.062}_{-0.053}$	$0.38^{+0.22}_{-0.16}$	0.003	0.027	0.350	0.620	0.269	1.000	1.000	764	396	396
6.364	(35107) 1991 VH	$1.12^{+0.23}_{-0.20}$	$0.27^{+0.20}_{-0.12}$	0.023	0.143	0.413	0.420	0.094	0.525	0.884	1311	554	427
6.379	(172974) 2005 YW55	$0.342^{+0.079}_{-0.059}$	$0.30^{+0.24}_{-0.13}$	0.000	0.103	0.383	0.513	0.269	0.901	1.000	772	421	400
6.405	(65679) 1989 UQ	$0.73^{+0.18}_{-0.15}$	$0.060^{+0.059}_{-0.028}$	0.647	0.270	0.077	0.007	0.144	0.530	1.000	1082	564	410
6.431	(159402) 1999 AP10	$1.20^{+0.29}_{-0.17}$	$0.35^{+0.23}_{-0.16}$	0.007	0.057	0.337	0.600	0.148	0.728	0.933	1033	466	412
6.491	(143651) 2003 QO104	$2.29^{+0.54}_{-0.51}$	$0.137^{+0.140}_{-0.061}$	0.160	0.380	0.327	0.133	0.243	0.639	1.000	826	509	407
6.507	1989 AZ	$1.09^{+0.20}_{-0.19}$	$0.025^{+0.019}_{-0.011}$	0.967	0.030	0.003	0.000	0.229	0.541	0.791	861	560	463
6.512	(218863) 2006 WO127	$1.70^{+0.40}_{-0.34}$	$0.21^{+0.17}_{-0.11}$	0.060	0.227	0.443	0.270	0.213	0.622	0.924	875	512	420
6.516	(140158) 2001 SX169	$0.58^{+0.16}_{-0.12}$	$0.26^{+0.19}_{-0.11}$	0.033	0.150	0.433	0.383	0.204	0.454	0.667	891	596	492
6.526	(100085) 1992 UY4	$2.60^{+0.70}_{-0.64}$	$0.020^{+0.022}_{-0.010}$	0.943	0.050	0.007	0.000	0.684	0.862	0.977	498	444	417
6.534	(85839) 1998 YO4	$1.81^{+0.42}_{-0.36}$	$0.174^{+0.136}_{-0.086}$	0.103	0.310	0.417	0.170	0.269	0.901	1.000	783	427	406

4.1. Reanalysis with updated H and G values for select objects

In the analysis above, we assume $G = 0.15$ and use H magnitudes from the *Horizons* ephemeris service. While both assumptions are known to be problematic, we are constrained to use them in the 'mass production' of diameters and albedo for practical reasons: we are not aware of a central database of published H and G values; rather, values for each target have to be searched in the literature and are unavailable for a large majority. In order to minimize the induced uncertainties, we reanalyze our data for objects with published H and/or G values; see Table 3. We focus on objects which we find to have low albedo, as well as Eros and Itokawa. Where available, we also include published determinations of the size, albedo, or taxonomic type. The results of this reanalysis are given in Table 4.

Low-albedo objects: For (175706) 1996 FG3, (65679) 1989 UQ, and (100085) 1992 UY4, our albedo results are low, as expected based on their known taxonomic classification. In the case of 1996 FG3, there is also an excellent quantitative match between our results and the ground-based measurements quoted in Table 3. Our diameter result for 1992 UY4 is formally in agreement with that by Volquardsen et al. (2007), provided that their value is assigned a realistic uncertainty of ~ 15 % to include systematic uncertainties (which are not discussed by the authors of that paper).

'Reality checks:' While the general agreement between ExploreNEOs results and other published diameter and albedo results is discussed by Harris et al. (2011), we consider it useful to check some of our results for low-Δv objects against published values. By comparing Tables 3 and 4, we find excellent agreement in the cases of (433) Eros, (25143) Itokawa, (10302) 1989 ML, (1943) Anteros, and (1627) Ivar.

(3671) Dionysus: Our nominal albedo result for Dionysus, $p_V = 0.55^{+0.21}_{-0.17}$, is hard to reconcile with its taxonimic classification as C_b type, for which a low albedo would be expected. Harris & Davies (1999) report UKIRT mid-IR observations of Dionysus from which they derive $p_V = 0.35$ or $p_V = 0.61$, depending on thermal model. Due to “inadequate signal-to-noise”, they were unable to constrain η from their data, like in our case. However, Harris & Davies also report ISO data, from which η can be constrained (if marginally so) to be ~ 3.1, in the upper range of plausible η values. This results in $p_V = 0.16$ (quoted after Harris & Lagerros 2002, —Harris & Davies reject that result in favor of another thermal model, leading to much higher albedo). We have therefore repeated the analysis of our Dionysus data assuming $\eta = 3$ (the phase angle of our observations, $\alpha = 62.6°$, is very similar to that of the ISO observations of Harris & Davies, 57.7°). The resulting albedo, $p_V = 0.178^{+0.092}_{-0.065}$, is in good agreement with Harris' NEATM result ($p_V = 0.16$) and consistent with a C_b classification given the error bars.

We note that binary NEOs including Dionysus were recently found to generally display higher-than-average η values (Delbo' et al. 2011), probably due to regolith loss during binary formation.

Table 2—Continued

Δv (km/s)	Object	D (km)	p_V	p_1	p_2	p_3	p_4	$q_{10\%}$ (AU)	$q_{50\%}$ (AU)	$q_{90\%}$ (AU)	$T_{10\%}$ (K)	$T_{50\%}$ (K)	$T_{90\%}$ (K)
6.539	(68359) 2001 OZ13	$0.62^{+0.15}_{-0.12}$	$0.42^{+0.27}_{-0.19}$	0.007	0.047	0.240	0.707	0.209	0.625	0.873	864	499	422
6.577	(11398) 1998 YP11	$1.73^{+0.47}_{-0.40}$	$0.176^{+0.185}_{-0.090}$	0.097	0.317	0.343	0.243	0.400	0.754	1.000	641	467	405
6.608	(155334) 2006 DZ169	$1.15^{+0.32}_{-0.29}$	$0.195^{+0.183}_{-0.095}$	0.080	0.253	0.387	0.280	0.275	0.803	1.000	771	451	404
6.609	(175706) 1996 FG3	$1.90^{+0.52}_{-0.44}$	$0.026^{+0.029}_{-0.012}$	0.923	0.067	0.010	0.000	0.307	0.531	0.730	743	565	482
6.610	(52760) 1998 ML14	$0.81^{+0.16}_{-0.14}$	$0.27^{+0.24}_{-0.11}$	0.007	0.140	0.413	0.440	0.456	0.731	0.895	594	469	424
6.628	(138947) 2001 BA40	$0.440^{+0.085}_{-0.080}$	$0.42^{+0.26}_{-0.18}$	0.003	0.053	0.213	0.730	0.205	0.484	0.723	871	567	464
6.652	2002 QE7	$0.320^{+0.061}_{-0.056}$	$0.34^{+0.20}_{-0.14}$	0.010	0.073	0.337	0.580	0.318	0.598	0.829	707	515	437
6.652	(5626) 1991 FE	$3.96^{+1.22}_{-0.92}$	$0.152^{+0.159}_{-0.081}$	0.173	0.323	0.340	0.163	0.644	1.000	1.000	507	406	406
6.661	(66251) 1999 GJ2	$0.90^{+0.24}_{-0.19}$	$0.37^{+0.30}_{-0.19}$	0.013	0.067	0.307	0.613	0.065	0.556	0.878	1558	533	424
6.692	(85990) 1999 JV6	$0.498^{+0.134}_{-0.088}$	$0.076^{+0.058}_{-0.035}$	0.500	0.373	0.120	0.007	0.142	0.457	0.629	1086	606	516
6.703	1998 SE36	$0.343^{+0.069}_{-0.072}$	$0.30^{+0.22}_{-0.14}$	0.027	0.127	0.347	0.500	0.209	0.348	0.666	875	678	490
6.738	(5645) 1990 SP	$2.20^{+0.74}_{-0.64}$	$0.062^{+0.079}_{-0.034}$	0.597	0.260	0.110	0.033	0.305	0.576	0.811	743	540	456
6.747	(3671) Dionysus	$0.89^{+0.11}_{-0.11}$	$0.67^{+0.37}_{-0.24}$	0.000	0.000	0.060	0.940	0.243	0.639	1.000	776	479	382
6.750	2002 HF8	$0.71^{+0.16}_{-0.15}$	$0.181^{+0.138}_{-0.081}$	0.090	0.300	0.410	0.200	0.759	1.000	1.000	465	405	405
6.751	(164202) 2004 EW	$0.157^{+0.024}_{-0.021}$	$0.36^{+0.22}_{-0.15}$	0.000	0.043	0.317	0.640	0.144	0.530	1.000	1048	546	397
6.757	2002 UN3	$0.310^{+0.052}_{-0.047}$	$0.67^{+0.35}_{-0.26}$	0.000	0.000	0.070	0.930	0.609	0.912	1.000	490	400	382
6.791	(90373) 2003 SZ219	$0.306^{+0.049}_{-0.049}$	$0.58^{+0.30}_{-0.23}$	0.000	0.013	0.060	0.927	0.269	0.901	1.000	747	408	387
6.817	(40329) 1999 ML	$0.96^{+0.23}_{-0.23}$	$0.154^{+0.157}_{-0.069}$	0.117	0.370	0.347	0.167	0.608	0.994	1.000	521	408	406
6.828	(6239) Minos	$0.474^{+0.117}_{-0.091}$	$0.56^{+0.39}_{-0.27}$	0.000	0.040	0.123	0.837	0.301	0.487	0.694	708	556	466
6.830	2005 EJ	$0.230^{+0.041}_{-0.038}$	$0.43^{+0.24}_{-0.19}$	0.000	0.033	0.243	0.723	0.318	0.598	0.829	700	510	433
6.840	(5646) 1990 TR	$2.03^{+0.52}_{-0.28}$	$0.65^{+0.43}_{-0.28}$	0.000	0.020	0.080	0.900	0.400	1.000	1.000	606	383	383
6.865	2003 WO7	$0.68^{+0.16}_{-0.13}$	$0.109^{+0.074}_{-0.051}$	0.277	0.480	0.210	0.033	0.400	1.000	1.000	646	408	408
6.867	1999 RH33	$0.228^{+0.042}_{-0.032}$	$0.73^{+0.35}_{-0.27}$	0.000	0.000	0.043	0.957	0.065	0.556	0.878	1488	509	405
6.963	2003 BT47	$1.15^{+0.31}_{-0.24}$	$0.147^{+0.149}_{-0.074}$	0.173	0.340	0.340	0.147	0.650	0.901	1.000	504	428	406
6.963	(10115) 1992 SK	$0.90^{+0.20}_{-0.18}$	$0.34^{+0.25}_{-0.13}$	0.003	0.050	0.360	0.587	0.129	0.491	0.754	1109	568	459
6.974	(5620) Jasonwheeler	$1.77^{+0.46}_{-0.40}$	$0.094^{+0.096}_{-0.046}$	0.360	0.373	0.223	0.043	0.400	1.000	1.000	647	409	409
6.981	(152563) 1992 BF	$0.51^{+0.12}_{-0.11}$	$0.084^{+0.077}_{-0.037}$	0.410	0.407	0.147	0.037	0.242	0.514	0.686	833	571	494
6.994	(138971) 2001 CB21	$0.578^{+0.109}_{-0.079}$	$0.24^{+0.12}_{-0.10}$	0.020	0.213	0.487	0.280	0.142	0.457	0.629	1068	596	508

Note. — p_1–p_4 denote the probability of the albedo falling within each of the four albedo bins described in the text (bin boundaries are 0.075, 0.15, and 0.3; primitive objects should display a high p_1). The last six columns, q_{xx} and T_{xx} describe the orbital and thermal history (see Section 5). E.g., $q_{10\%}$ denotes the minimum perihelion distance that the object reached to within a probability of 10%, $T_{10\%}$ is the corresponding temperature to which the surface was heated. Note that some of the diameter and albedo results herein are superseded in Table 4.

Table 3. Published physical properties for objects considered in Sect. 4.1

Object	H	G	D(km)	p_V	Bin[a]	Taxo[b]	Reference
(433) Eros[c]	10.46 ± 0.10	0.18	23.6[a]	0.22[b]	–	S	1,2
(25143) Itokawa	$19.51^{+0.09}_{-0.08}$[c]	$0.29^{+0.07}_{-0.06}$	0.327 ± 0.006	0.26 ± 0.02	–	S(IV)	3,4
(10302) 1989 ML	—	—	0.28 ± 0.05	0.37 ± 0.15	–	E	5
(175706) 1996 FG3	17.76 ± 0.03	-0.07	~ 1.9	~ 0.04	Y	C	6,7,8
(1943) Anteros	15.9 ± 0.2	0.23	~ 2.2	~ 0.16	–	L	9,10,11
(65679) 1989 UQ	19.5 ± 0.3	—	—	—	–	B	11,12
(162998) 2001 SK162	—	—	—	—	–	T	11
(100085) 1992 UY4	17.71 ± 0.10	—	1.7	0.05	–	P	13,14
(152563) 1992 BF	—	—	—	—	–	X_c	15
(12923) Zephyr	—	—	—	—	–	S	16
(1627) Ivar	12.87 ± 0.10	—	9.1 ± 1.4	0.15 ± 0.05	–	S	16,17
(85990) 1999 JV6	—	—	—	—	–	X_k	15
(3671) Dionysus	16.66 ± 0.30	—	1.1–1.5	0.16–0.31	Y	C_b	15,18,19

[a]Y indicates that the object is known to be binary

[b]Taxonomic type

[c]See Trilling et al. (2010) for a discussion of the values adopted for Eros, which was observed at a nearly pole-on viewing geometry, and Mueller (2007) for a discussion of its G value.

References. — (1) Harris & Davies (1999); (2) Li et al. (2004); (3) Bernardi et al. (2008); (4) Volume-equivalent diameter calculated from the volume given by Demura et al. (2006); (5) Mueller et al. (2007); (6) Pravec et al. (2006); (7) Mueller et al., in preparation; (8) Binzel et al. (2001); (9) Adopted after 15.82 ± 0.14(Wisniewski et al. 1997) and 15.96 ± 0.14 (Pravec et al. 1998), both give $G = 0.23$; (10) Quoted after Harris et al. (2011), original data from Veeder et al. (1989); (11) Binzel et al. (2004a); (12) Pravec et al. (1998); (13) Warner et al. (2006)—no H uncertainty is given by Warner et al., 0.1 mag seems appropriate (or slightly conservative) given the low scatter of their data; (14) Volquardsen et al. (2007)—note that their error bars (not quoted herein) reflect only the statistical uncertainties, but not the systematics; (15) Bus & Binzel (2002); (16) Binzel et al. (2004b); (17) Delbo' et al. (2003) determined D and p_V of Ivar based on Keck mid-IR photometry, we here assume a 15% uncertainty in D and 30% in p_V as is usual for radiometric diameters. H is from Pravec et al. (unpublished), quoted after Delbo' et al. (2003). (18) Different, model-dependent, diameter and albedo values are given by Harris & Davies (1999); Harris & Lagerros (2002)—we quote the range of their adopted results. Harris & Davies (1999) quote Pravec (unpublished) for the H given herein, no uncertainty value is stated, we assume a conservative uncertainty of 0.3 mag. (19) Mottola et al. (1997)

This may be expected to reduce the accuracy of our results for binaries in general. However, in the case of the only other known low-albedo binary, 1996 FG3 (see above), our results are quite consistent with those obtained otherwise.

5. Thermal history

It is well known that implantation of solar wind ions (Hapke 2001) and bombardment by micrometeorites can alter the spectroscopic properties of asteroids (Sasaki et al. 2001). However, these aging processes affect only the topmost microns of the surface. This is not a problem for a sample collection experiment: current-technology sampling devices can sample material from a depth of a few centimeters, thus excavating below the space-weathered surface.

However, Marchi et al. (2009) have shown that the surfaces of a significant number of NEOs were heated by the Sun to very high temperatures that could induce surface alterations on previously primitive objects. Due to thermal conduction, a thin layer beneath the surface can be heated to similarly large temperatures; for typical thermal properties (Mueller 2007; Delbo' et al. 2007) and rotation periods, the penetration depth of the heat wave is of the order of centimeters (Spencer et al. 1989), comparable to the digging depth of sample-taking devices.

There is no clear-cut way to determine the maximum temperature to which an asteroid can be heated and remain in primitive condition. From laboratory studies of carbonaceous chondrite meteorites, to which primitive asteroids are generally believed to be related, we know different alteration processes that are characterized by different threshold temperatures (e.g. thermal breakup of organic macromolecules). For instance, it has been determined by laboratory heating experiments that at 370 K the insoluble organic matter of the carbonaceous meteorite Murchinson is degraded (the aliphatic C-H bond is lost) in approximately 200 years (Kebukawa et al. 2010). The same authors also showed that the bulk organics of Murchinson are lost in only one year at 370 K (or 200 years at 300 K). It is also known that the macromolecular phase in carbonaceous meteorites has a structure similar to refractory kerogen. The latter starts to break up - with production of oil and gas - when heated above 420 K (I. Franchi 2008, personal communication). Furthermore, Lauretta et al. (2001) have shown experimentally that volatile components (such as Hg) are released from some CM and CV carbonaceous chondrites when the latter are heated above $\sim$ 470 K.

The maximum temperature attained by an NEO is a function of the perihelion distance q. NEO orbits can evolve rapidly (see, e.g., Michel & Froeschlé 1997), hence the present q is not particularly indicative of the minimum q attained within the chaotic dynamical history. Hence, if it is a goal to send a spacecraft to a primitive object, the dynamical and thermal history of the target must be taken into account.

An upper limit on the subsurface temperature is the surface temperature at local noon. Because spin axes of NEOs evolve on relatively short timescales (e.g. due to YORP, planetary encounters,

and possibly due to spin-orbit coupling) the whole surface is likely to have been subjected to temperatures (nearly) as high as that of the subsolar point, T_{SS}. We calculate T_{SS} as a function of q using the NEATM (see Section 3), assuming the nominal albedo resulting from our Spitzer observations and $\eta = 0.91$. That latter value follows from Equation (1) for $\alpha = 0$, hence providing an upper limit on temperature.

With this in mind, the maximum surface temperature attained follows from the minimum q reached in the past. Due to the chaotic nature of NEO orbits, this question must be treated probabilistically. We here use the orbital evolution model by Marchi et al. (2009), which was derived from Bottke et al. (2000, 2002). For each of our targets, we extract from the work by Marchi et al. the probabilities that the object reached a perihelion distance smaller than a grid of q values. Through interpolation, we determine $q_{50\%}$, i.e. the q value which was reached with a probability of 50%. We call the corresponding subsolar temperature $T_{50\%}$. The odds are 50% that an object ventured to within $q_{50\%}$ of the Sun and that its surface was heated to $T_{50\%}$ or more. We repeat this exercise for probability values of 10 and 90%; results are given in Table 2.

Note, for instance, that (65679) 1989 UQ certainly appears primitive judging from its low albedo (this work) and its spectroscopic classification as B type (Binzel et al. 2004a). 1989 UQ was considered repeatedly as a target of sample-return mission concepts to a primitive asteroid. However, we show that this object has likely been heated to the point that its organic macromolecular matter has been broken up ($T_{50\%} = 564$ K—cf. Table 2). The same applies to the binary system (175706) 1996 FG3.

However, the final determination whether an object is to be considered primitive or not is beyond our scope. Rather, our aim is to provide the required input data for that determination. Given that objects may have exceeded some but not all of the threshold temperatures discussed above, the exact definition of 'primitive' depends on the scientific purpose at hand. Also, it is incumbent on the mission-design team to quantify the risk they are willing to take (note the probabilistic nature of our temperature determinations due to the chaotic orbital history of NEOs).

6. Discussion

6.1. Updated ExploreNEOs thermal-modeling pipeline

For a fraction of our targets, our data have been published previously along with a straightforward NEATM analysis (Trilling et al. 2010; Harris et al. 2011). Due to the updates in the thermal-modeling pipeline presented in Section 3.1, our results given in Table 2 supersede previous values where available. This difference, however, is always comfortably within the quoted error bars and too small to matter practically. A new analysis of the entire data set including new observations will be presented in a later paper.

The new pipeline provides estimates of the statistical uncertainty of diameter and albedo

results. The uncertainties are distributed in a highly non-Gaussian way, especially for p_V, hence asymmetric "1σ" error bars are given. Additionally, we provide probabilities of p_V to fall into specific bins, which allows for more straightforward constraints on the taxonomic type and hence surface mineralogy.

6.2. Potential spacecraft targets

1996 XB27 and 1989 ML: These bodies are, along with the Hayabusa target Itokawa, the only objects with $\Delta v < 5$ km/s within our sample. We find both objects to be very high in albedo, indicative of taxonomic types such as E (1989 ML was found to be E type by Mueller et al. 2007). The chances of them being primitive are very small. With a diameter of only 84^{+13}_{-12} m, 1996 XB27 is among the smallest celestial objects with known size.

Primitive objects: Some of our albedo results suggest a primitive composition. We adopt a threshold value of 50% for p_1, the probability of $p_V < 7.5$ %. A list of all measured physical properties of these objects is compiled in Table 5. There are significant object-to-object differences in thermal history. As discussed in Section 5, there is no clearly defined threshold temperature above which primitive material is metamorphosed. The least heated objects (at the 50% probability level) are 1992 UY4, 2001 SK162, and 2001 PM9. 1996 FG3 is the only known binary in the low-p_V sample.

7. Conclusions

Of the 293 NEOs observed within the framework of our ongoing ExploreNEOs survey as of 2010 July 14, 65 have $\Delta v \leq 7$ km/s. Diameter and albedo measurements for the latter are presented in this work. Assuming that the rate of observations of low-Δv objects stays as it is, the number of observed low-Δv objects will increase to ~ 160 by the end of ExploreNEOs, i.e. before the end of 2011. Teams requiring a physical characterization of potential spacecraft targets are encouraged to contact us.

Out of our 65 low-Δv targets, 7 have low albedos indicating a primitive surface composition. These objects include a binary (1996 FG3) and three objects which stayed remarkably cool during their dynamical history, possibly cool enough to remain primitive: 1992 UY4, 2001 SK162, and 2001 PM9.

Michael Mueller gratefully acknowledges the Henri Poincaré Fellowship, which is funded by the CNRS-INSU and the Conseil Général des Alpes-Maritimes. The work of MM and MD is supported by ESA grant SSA-NEO-ESA-MEM-017/1. We thank Patrick Michel for helpful discussions. This

Table 4. Reanalysis of thermal data with updated H and G values (see Table 3)

Object	D(km)	p_V	p_1	p_2	p_3	p_4	D^*	$p_V{}^*$
(433) Eros	$23.0^{+8.3}_{-5.6}$	$0.218^{+0.173}_{-0.099}$	0.030	0.250	0.423	0.297	$30.7^{+10.0}_{-8.3}$	$0.065^{+0.075}_{-0.034}$
(25143) Itokawa	$0.313^{+0.054}_{-0.044}$	$0.283^{+0.116}_{-0.075}$	0.000	0.023	0.550	0.427	$0.319^{+0.045}_{-0.050}$	$0.41^{+0.20}_{-0.18}$
(10302) 1989 ML	$0.240^{+0.043}_{-0.038}$	$0.50^{+0.21}_{-0.18}$	0.003	0.010	0.127	0.860	$0.248^{+0.035}_{-0.043}$	$0.47^{+0.28}_{-0.19}$
(175706) 1996 FG3	$1.84^{+0.56}_{-0.47}$	$0.042^{+0.035}_{-0.017}$	0.837	0.140	0.023	0.000	$1.90^{+0.52}_{-0.44}$	$0.026^{+0.029}_{-0.012}$
(1943) Anteros	$2.38^{+0.72}_{-0.59}$	$0.138^{+0.107}_{-0.061}$	0.150	0.420	0.367	0.063	$2.48^{+0.69}_{-0.60}$	$0.145^{+0.146}_{-0.073}$
(65679) 1989 UQ	$0.72^{+0.18}_{-0.14}$	$0.053^{+0.036}_{-0.021}$	0.753	0.223	0.023	0.000	$0.73^{+0.18}_{-0.15}$	$0.060^{+0.059}_{-0.028}$
(100085) 1992 UY4	$2.50^{+0.67}_{-0.58}$	$0.0230^{+0.0190}_{-0.0090}$	0.977	0.020	0.003	0.000	$2.60^{+0.70}_{-0.64}$	$0.020^{+0.022}_{-0.010}$
(1627) Ivar	$9.9^{+2.8}_{-2.8}$	$0.128^{+0.123}_{-0.052}$	0.157	0.447	0.273	0.123	$9.4^{+3.9}_{-2.3}$	$0.094^{+0.138}_{-0.051}$
(3671) Dionysus	$0.86^{+0.12}_{-0.11}$	$0.55^{+0.21}_{-0.17}$	0.000	0.000	0.047	0.953	$0.89^{+0.11}_{-0.11}$	$0.67^{+0.37}_{-0.24}$
Dionysus with $\eta = 3$	$1.46^{+0.21}_{-0.18}$	$0.179^{+0.092}_{-0.065}$	0.020	0.320	0.553	0.107	···	···

Note. — In the last two columns, the diameter and albedo results for the 'nominal' H and G values are given for comparison (see Table 2). In this reanalysis, $\eta = 1.07$ is assumed for (433) Eros (see Trilling et al. 2010). Two η assumptions are made for (3671) Dionysus, the one used in the rest of this manuscript (see Equation (1); upper line), and $\eta = 3$ (lower line). For all objects except Eros and Dionysus, D and D^* values are practically indistinguishable, implying that diameter results are not significantly impacted by the H uncertainty.

Table 5. Potentially primitive objects as indicated by their low albedo ($p_1 > 50$ %)

Δv (km/s)	Object	p_1	D (km)	p_V	$T_{10\%}$ (K)	$T_{50\%}$ (K)	$T_{90\%}$ (K)	Taxo
5.565	(162998) 2001 SK162	0.92	1.9 ± 0.4	$0.03^{+0.03}_{-0.02}$	834	462	418	T
5.653	(68372) 2001 PM9	0.97	1.7 ± 0.5	$0.018^{+0.017}_{-0.008}$	782	488	441	–
6.405	(65679) 1989 UQ	0.75	0.7 ± 0.2	$0.05^{+0.04}_{-0.02}$	1082	564	410	B
6.507	1989 AZ	0.97	1.1 ± 0.2	$0.03^{+0.02}_{-0.01}$	861	560	463	–
6.526	(100085) 1992 UY4	0.98	$2.5^{+0.7}_{-0.6}$	$0.023^{+0.019}_{-0.009}$	498	444	417	P
6.609	(175706) 1996 FG3	0.84	$1.8^{+0.6}_{-0.5}$	$0.04^{+0.04}_{-0.02}$	743	565	482	C
6.738	(5645) 1990 SP	0.60	$2.2^{+0.8}_{-0.7}$	$0.06^{+0.08}_{-0.04}$	743	540	456	–

Note. — See Table 2 for the definition of p_1. Where available, diameter and albedo results are from the reanalysis in Table 4, otherwise from Table 2. As discussed in Section 5, the chances are 10/50/90 % that the surface temperature has reached $T_{10/50/90\%}$ or above.

work is based in part on observations made with the Spitzer Space Telescope, which is operated by JPL/Caltech under a contract with NASA. Support for this work was provided by NASA through an award issued by JPL/Caltech.

Facilities: Spitzer(IRAC)

REFERENCES

Abell, P.A., et al., 2009, Meteoritics & Plan. Sci, 44, 1825

Bernardi, F., Tholen, D.J., Micheli, M., 2008, In: ACM meeting 2008.http://www.lpi.usra.edu/meetings/acm2008/pdf/8338.pdf

Binzel, R.P., Harris, A.W., Bus, S.J., Burbine, T.H., 2001, Icarus, 151, 139

Binzel, R.P., Perozzi, E., Rivkin, A.S., Rossi, A., Harris, A.W., Bus, S.J., Valsecchi, G. B., & Slivan, S. M. 2004a, Meteoritics & Plan. Sci., 39, 351

Binzel, R.P., Rivkin, A.S., Stuart, J.S., Harris, A.W., Bus, S.J., Burbine, T.H., 2004b, Icarus, 170, 259

Bottke, W.F., Jedicke, R., Morbidelli, A., Petit, J.-M., Gladman, B., 2000, Science, 288, 2190

Bottke, W.F., Morbidelli, A., Jedicke, R., Petit, J.-M., Levison, H.F., Michel, P., Metcalfe, T.S., 2002, Icarus, 156, 399

Bus, S.J. & Binzel, R.P., 2002, Icarus, 158, 146

Carey, S.J., et al., 2010, Proc. SPIE, 7731, 77310N

Delbo', M., Harris, A.W., Binzel, R.P., Pravec, P., Davies, J.K., 2003, Icarus, 166, 116

Delbo', M., dell'Oro, A., Harris, A.W., Mottola, S., Mueller, M. 2007, Icarus, 190, 236

Delbo', M., Walsh, K., Mueller, M., Harris, A.W., Howell, E.S., 2011, Icarus, in press

Demura, H., et al., 2006, Science, 312, 1347

Fazio, G. G. et al. 2004, ApJS, 154, 10

Fernández, Y.R., Jewitt, D.C., Sheppard, S.S., 2005, AJ, 130, 308

Hahn, G., et al., 1989, Icarus, 78, 363

Hapke, B. 2001, J. Geophys. Res., 106(E5), 10,039–10,073

Harris, A.W. 1998, Icarus, 131, 291

Harris, A. W. & Davies, J. K. 1999, Icarus, 142, 464

Harris, A.W. & Lagerros, J.S.V., 2002, Asteroids III, 205

Harris, A.W. & Harris, A.W. 1997, Icarus, 126, 450

Harris, A.W., Mueller, M., Lisse, C.M., & Cheng, A.F. 2009, Icarus, 199, 86

Harris, A.W., et al., 2011, AJ, in press (ExploreNEOs II)

Jurić, M., et al. 2002, AJ, 124, 1776

Kebukawa, Y., Nakashima, S., Zolensky, M.E. 2010. Meteoritics and Planetary Science 45, 99-113.

Lauretta, D. S., Klaue, B., Blum, J. D., & Buseck, P. R. 2001., in Lunar and Planetary Institute Science Conference Abstracts, 32, ed. LPI Ed. Board (Houston: LPI), 1356.

Lauretta, D.S., et al. 2010. In: 73rd Annual Meteoritical Society Meeting, http://www.lpi.usra.edu/meetings/metsoc2010/pdf/5153.pdf

Li, J., A'Hearn, M. F., & McFadden, L. A. 2004, Icarus, 172, 415

Marchi, S., Delbo', M., Morbidelli, A., Paolicchi, P., Lazzarin, M. 2009, MNRAS, 400, 147

Michel, P., & Froeschlé, C. 1997, Icarus, 128, 230

Michel, P., et al. 2009. In: 72nd Annual Meeting of the Meteoritical Society, http://www.lpi.usra.edu/meetings/metsoc2009/pdf/5261.pdf

Mottola, S., Hahn, G., Pravec, P., Šarounová, L., 1997. IAU Circ. 6680.

Mueller, M. 2007, Ph.D. Thesis, Freie Universität, Berlin, http://www.diss.fu-berlin.de/2007/471/indexe.htm

Mueller, M., Harris, A.W., & Fitzsimmons, A. 2007, Icarus, 187, 611

Okada, T., et al., in 41st LPSC meeting, http://www.lpi.usra.edu/meetings/lpsc2010/pdf/2132.pdf

Parker, A., Ivezić, Ž., Jurić, M., Lupton, R., Sekora, M.D., Kowalski, A. 2008. Icarus, 198, 138

Pravec, P., Wolf, M., Šarounová, L., 1998, Icarus, 136, 124

Pravec, P., et al., 2006. Icarus, 181, 63.

Ryan, E.L. & Woodward, C.E. 2010. AJ, 140, 933

Sasaki, S., Nakamura, K., Hamabe, Y., Kurahashi, E., & Hiroi, T. 2001, Nature, 410, 555

Shoemaker, G. & Helin, E. 1978, NASA CP-2053, pp. 245-256. http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19780021079_1978021079.pdf

Spencer, J. R., Lebofsky, L. A., & Sykes, M. V. 1989, Icarus (ISSN 0019-1035), 78, 337

Trilling, D. E., Mueller, M., Hora, J. L., Fazio, G. G., Spahr, T., Stansberry, J. A., Smith, H. A., Chesley, S. R., & Mainzer, A. K. 2008, ApJ, 683, L199

Trilling, D. E., et al., C2010, AJ, 140, 770 (ExploreNEOs I)

Veeder, G.J., Hanner, M.S., Matson, D.L., Tedesco, E.F., Lebofsky, L.A., Tokunaga, A.T., 1989, AJ, 97, 1211

Volquardsen, E.L., Rivkin, A.S., Bus, S.J., 2007, Icarus, 187, 464

Warner, B.D., Jacques, C., Pimentel, E., Crawford, G., Behrend, R., Klotz, A., Stoss, R., Nomen, J., Sanchez, S., 2006, Minor Planet Bull., 33, 20

Werner, M.W. et al. 2004, ApJS, 154, 1

Wisniewski, W.Z., Michałowski, T.M., Harris, A.W., McMillan, R.S., 1997, Icarus, 126, 395

Wolters, S.D., Green, S.F., McBride, N., Davies, J.K. 2008, Icarus, 193, 535